

THE EFFECT OF THE SSW/ES 2018 ON THE VLF SIGNAL OF THREE TX-RX LINKS IN HIGH LATITUDES

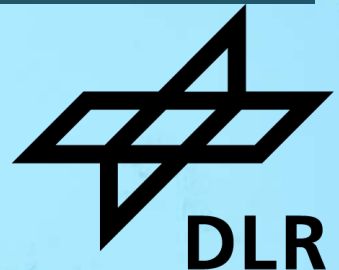
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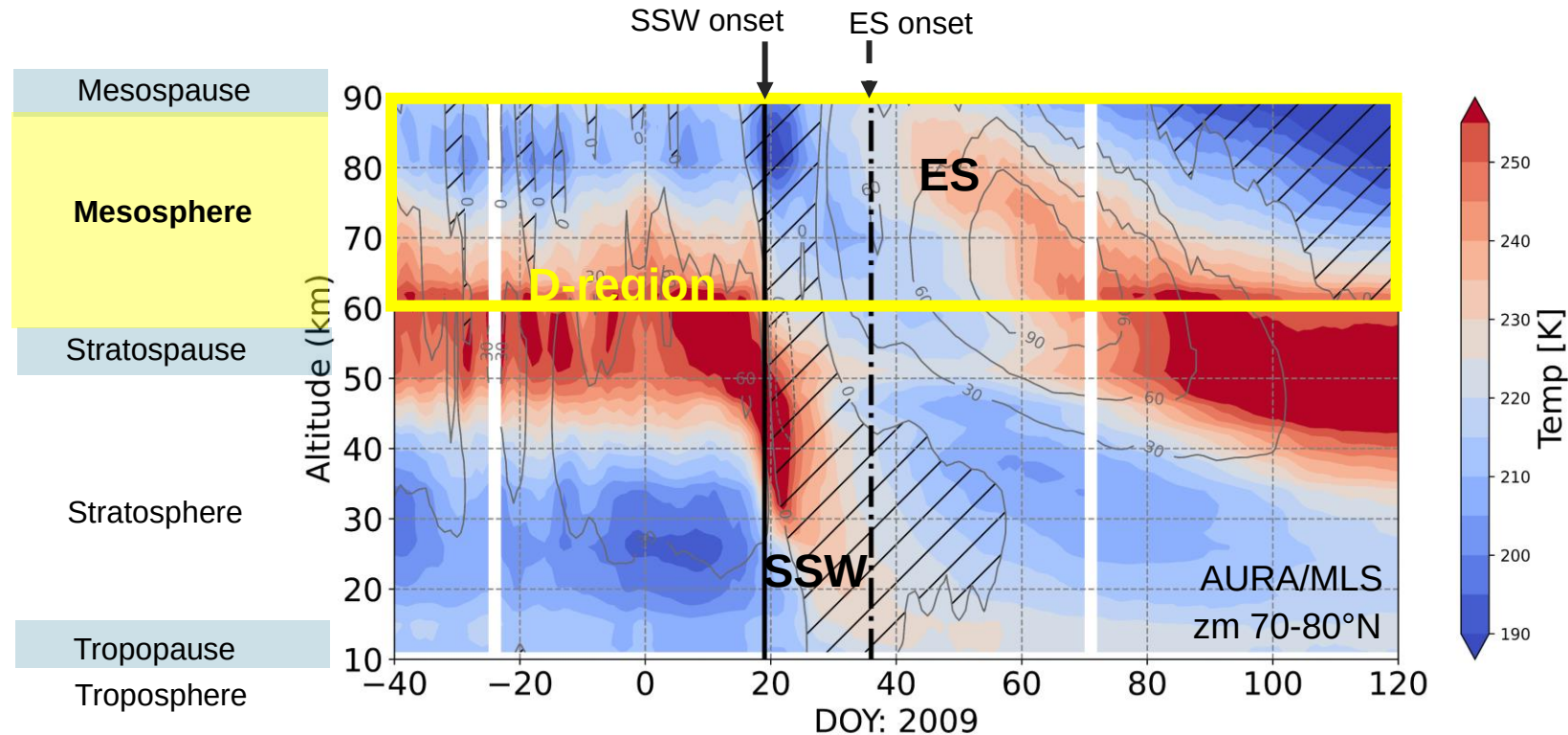
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Sudden Stratospheric Warming & Elevated Stratopause events



- significant anomalies in wind, temperature and vertical mass transport in stratosphere and mesosphere
- Mesosphere and ionospheric D-region overlap

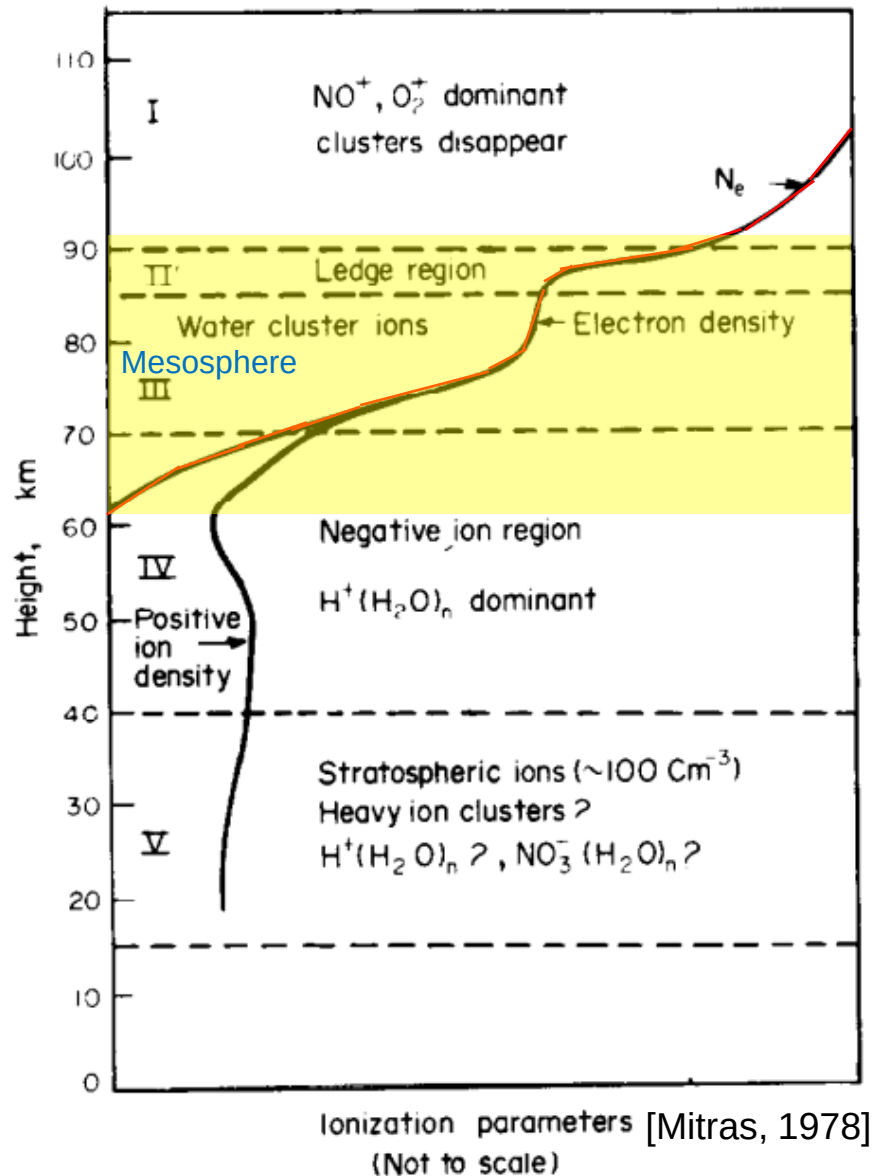
SSW anomalies in mesosphere:

- temperature decrease
- windreversal: westward wind
- water vapor increase

ES anomalies in mesosphere:

- temperature increase
- strong eastward wind
- water vapor decrease
- NO increase

D-region and VLF signal

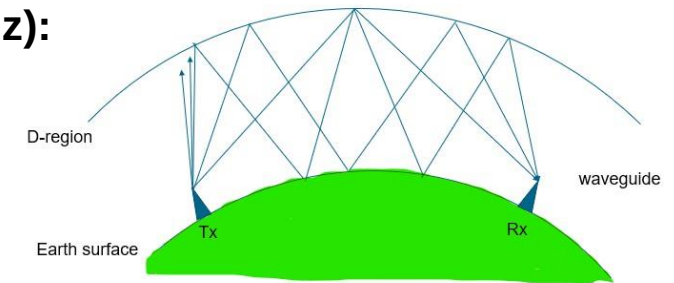


D-region (60-90 km):

- photoionization of NO by Lyman- α radiation
- heavy water cluster ions + negative ions
- water cluster ions recombine quickly with inverse dependency on Temp
- 82-85 km: sharp 'ledge' in N_e , with an increase of almost an order magnitude within a few km

Very Low Frequency signal (VLF, 3-30 kHz):

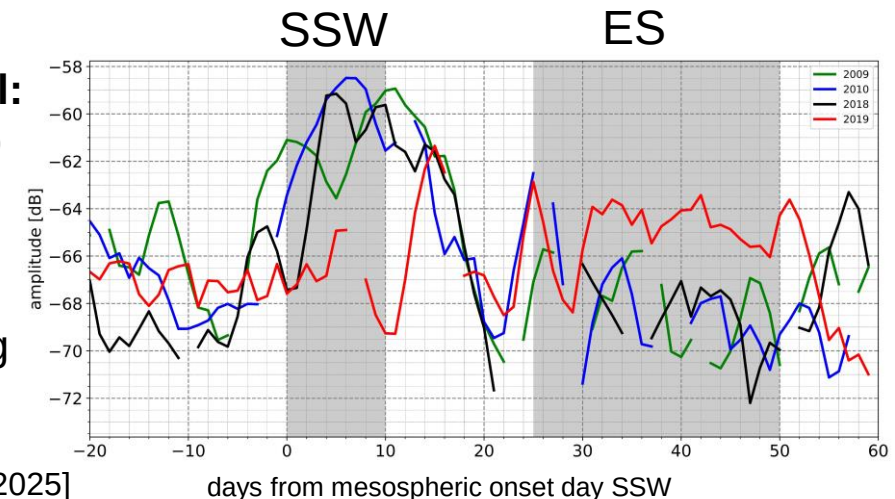
- propagates from Tx to Rx within earth-ionospheric waveguide
- D-region is upper reflection boundary
- changes in D-region ionization are notable in VLF signal



SSW/ES impact on VLF signal:

- High latitude link (NRK-NYA)
- Similar VLF amplitude anomalies during 3 SSW/ES events
- an amplitude increase during SSW and a decrease during the ES period

[Schneider et al., 2025]



Mechanism

[Schneider et al., 2025]

amplitude increase

SSW: increased water clusters + decreased Temp
 -> decrease of Ne below ledge region
 -> sharp edge in Ne profile: increase of Ne gradient β and of the effective reflection height h'
 -> amplitude increase (LWPC)

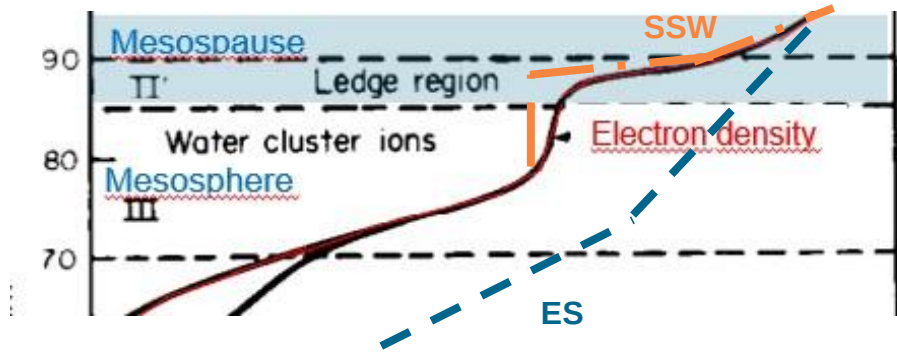
SSW: decreased Temp decreases collision frequency -> less absorption of the signal

amplitude decrease

ES: decreased H_2O + increased Temp lead to increase Ne below ledge

ES: NO, dragged down to lower altitudes during the ES, causes increased Ne
 -> decrease of β and h'
 -> amplitude decrease (LWPC)

ES: increased Temp increases collision frequency -> stronger absorption of the signal

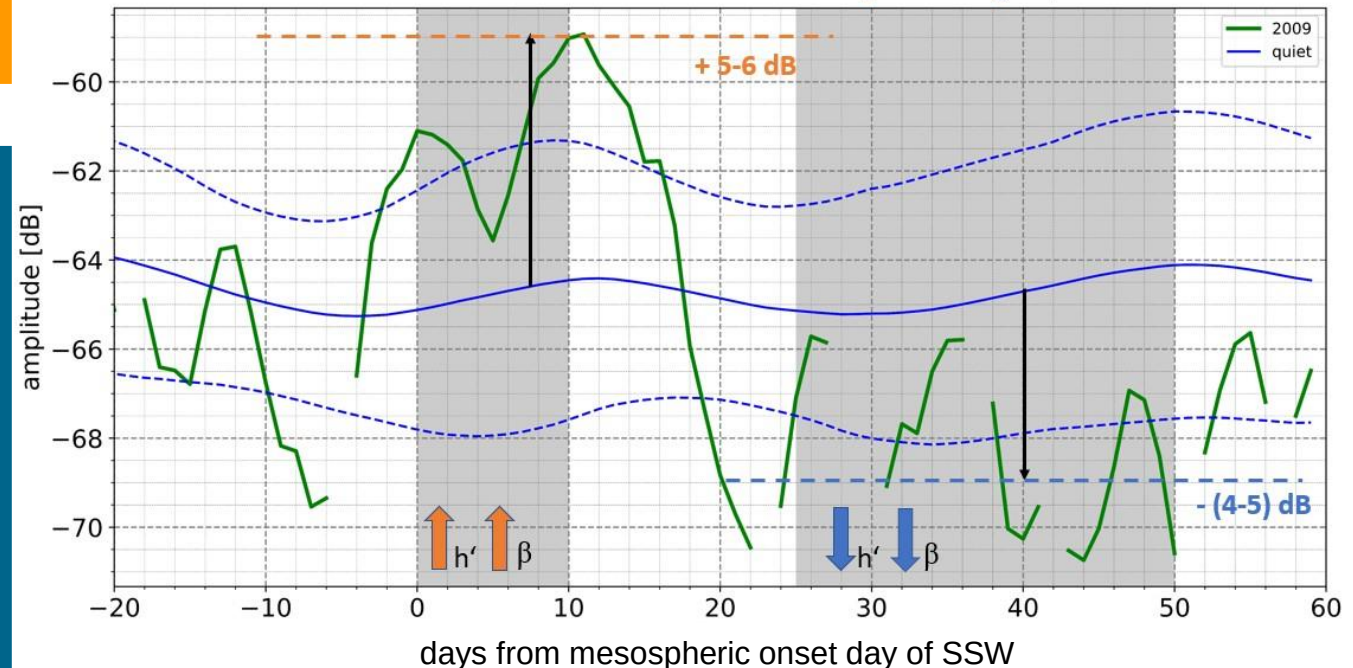


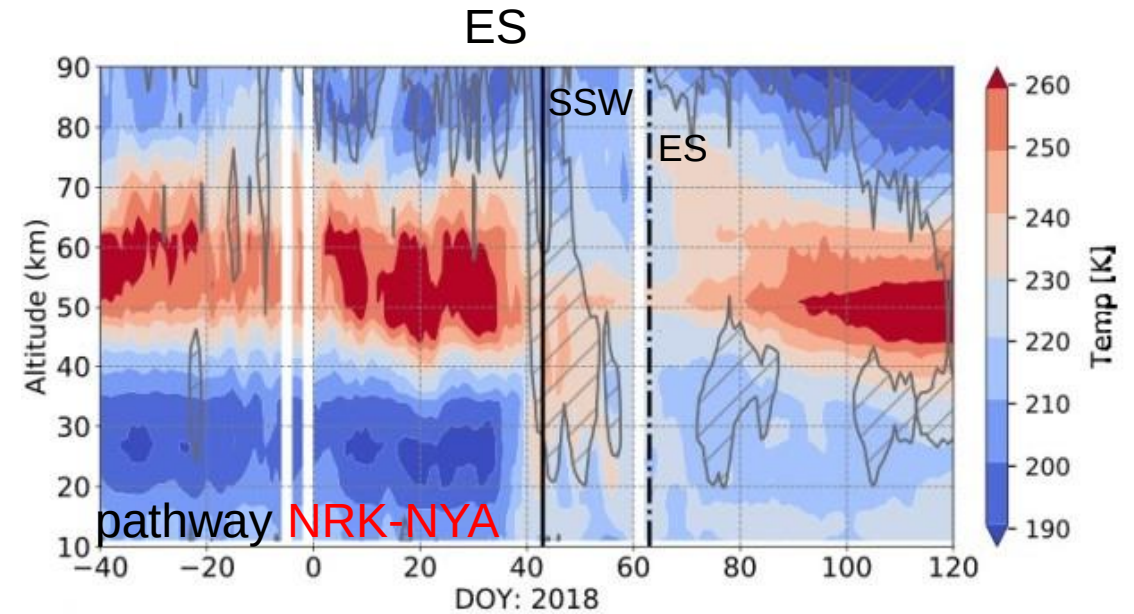
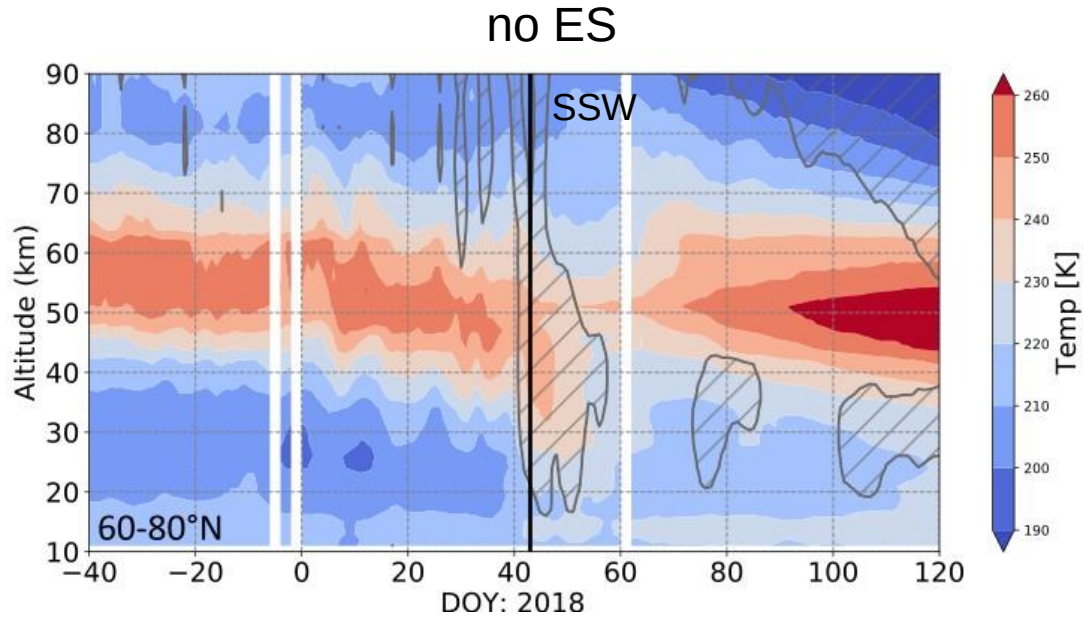
SSW period

↑ H_2O → ↑ α_{eff}
 ↓ T → ↑ α_{eff}
 ↓ T → ↓ v

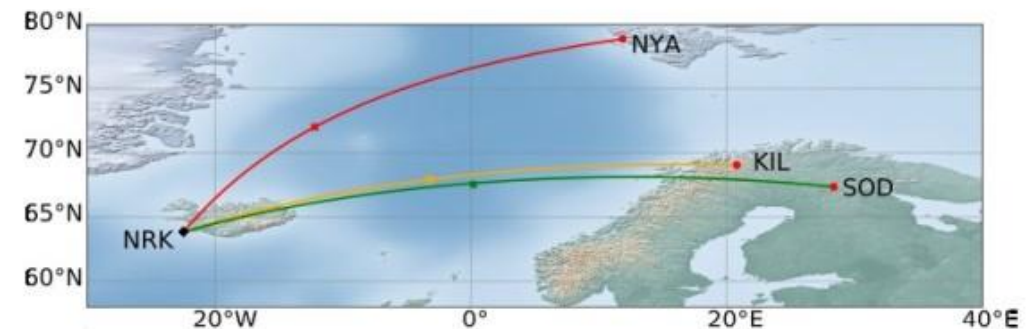
ES period

↓ H_2O → ↓ α_{eff}
 ↑ T → ↓ α_{eff}
 ↑ T → ↑ v
 ↑ NO → ↑ N_e



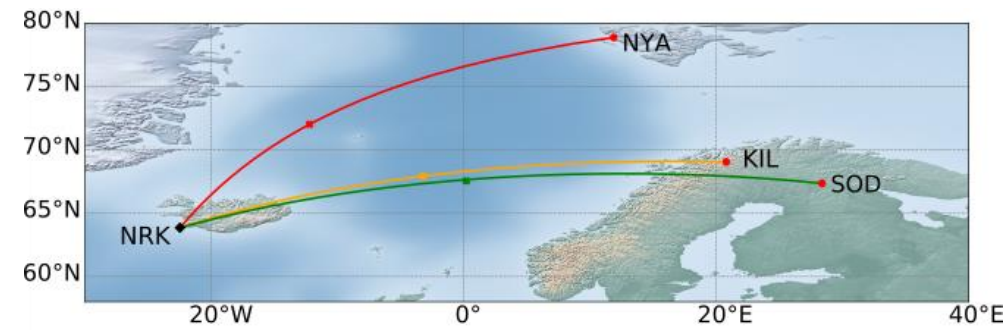
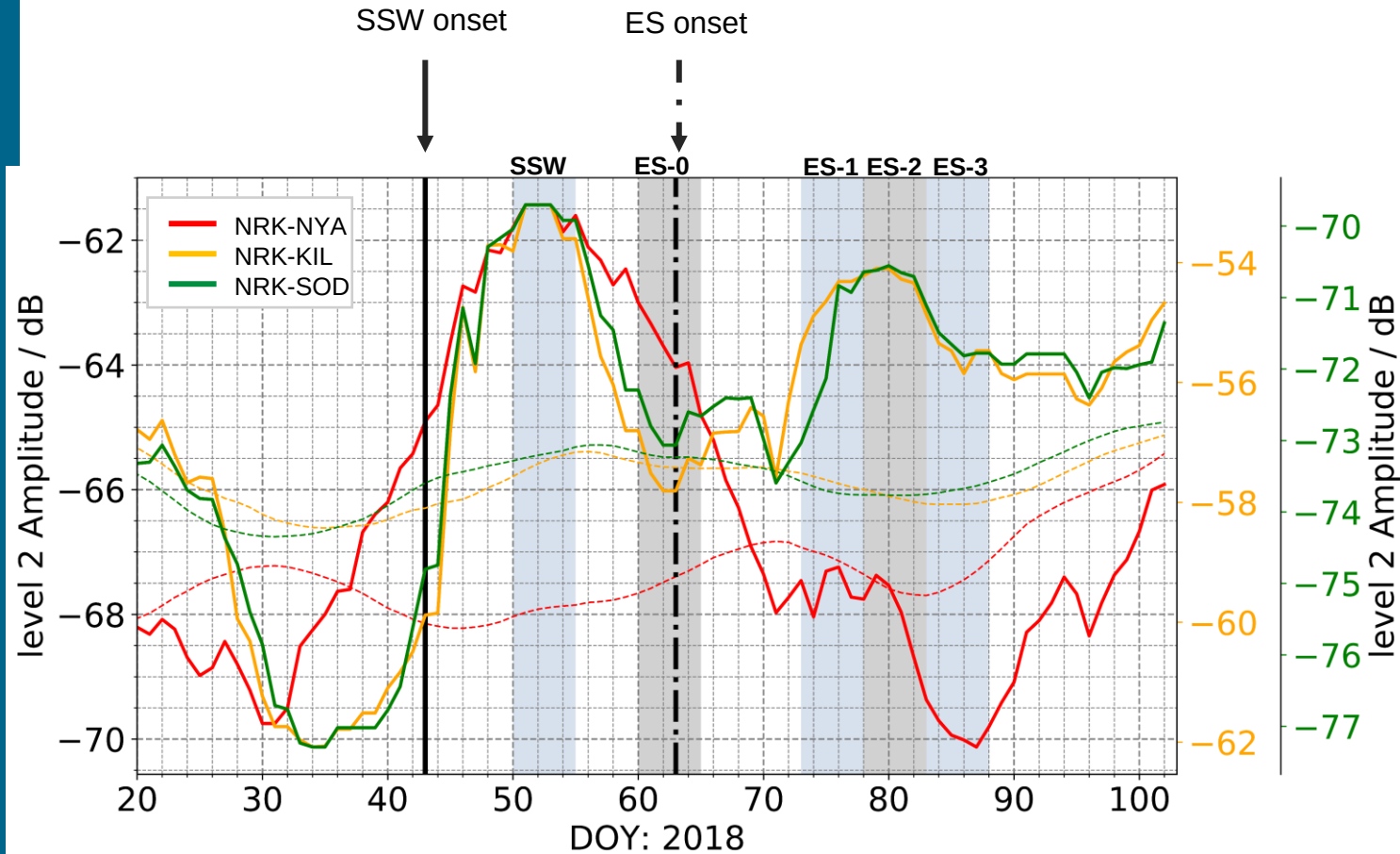


- SSW event in 2018 is notable in the zonal average from 60-80°N, ES event is not notable
- But, ES event is locally notable, e.g., in the average along the pathway for NRK-NYA
- Does spatial variability of ES event affect the VLF signal amplitude?



NRK: 37.5 kHz, all 3 receivers part of the AARDDVARK network

VLF signal amplitude variation of three Tx-Rx links

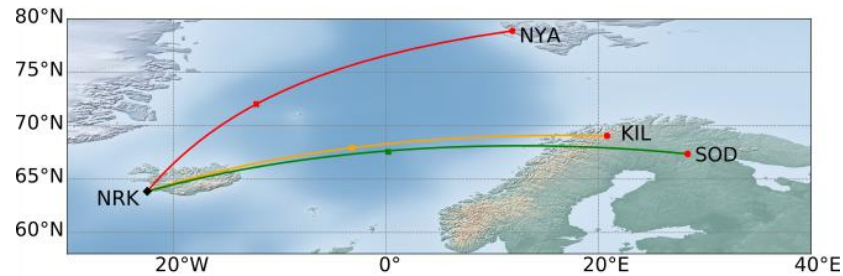


- NRK-KIL and NRK-SOD very similar variation, due to the similar pathway
- all three links show an amplitude increase around SSW onset until they peak around DOY 50

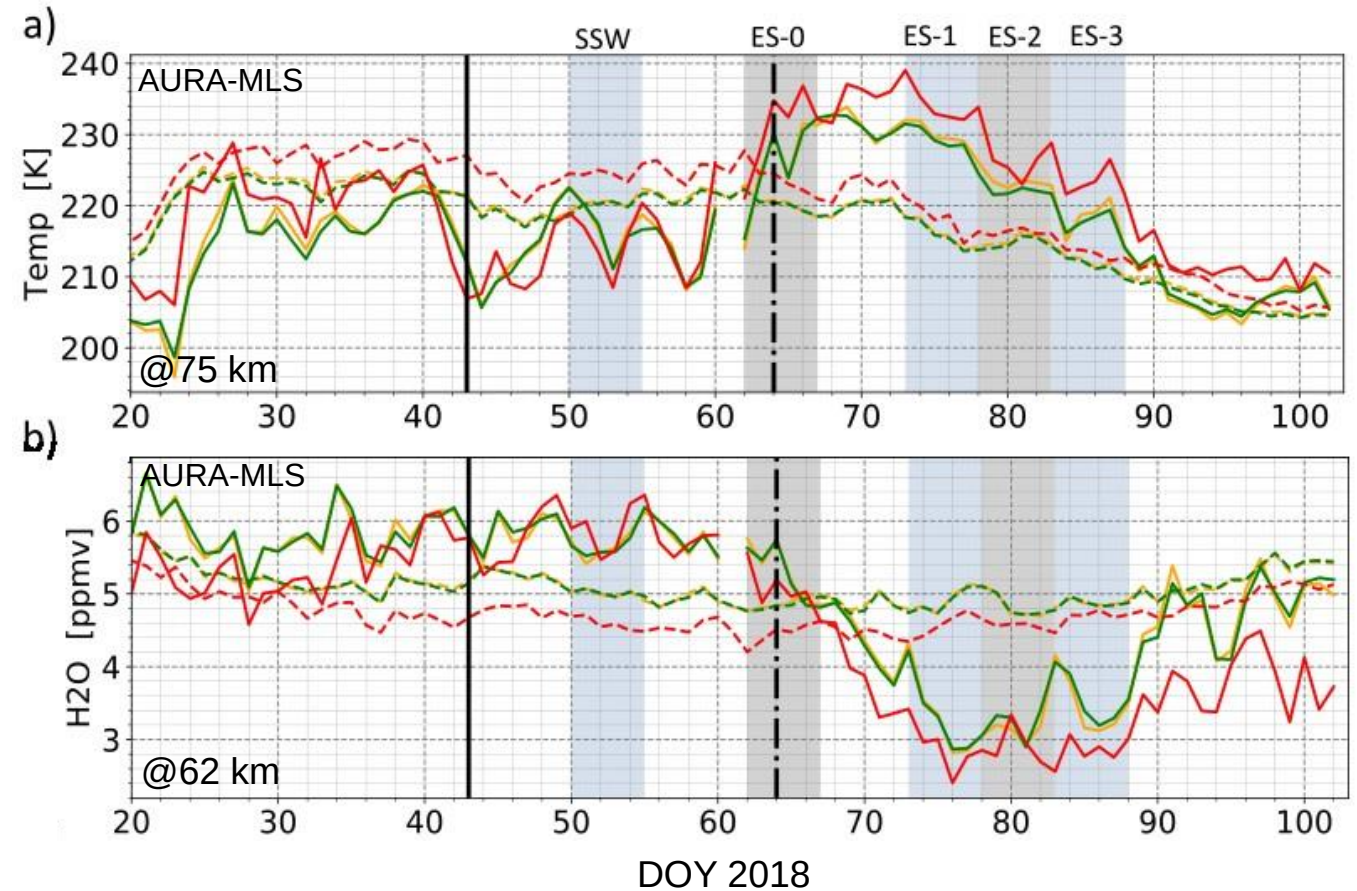
Differences:

- NRK-NYA: amplitude decreases from almost until DOY 90, interrupted by short stagnation
- NRK-KIL/SOD: amplitude decreases from SSW peak until beginning of the ES
- NRK-KIL/SOD: increases until DOY 80, followed by decrease
- Differences begin at ES-0 and become strongest during ES-1, ES-2 and ES-3

Atmospheric Parameters



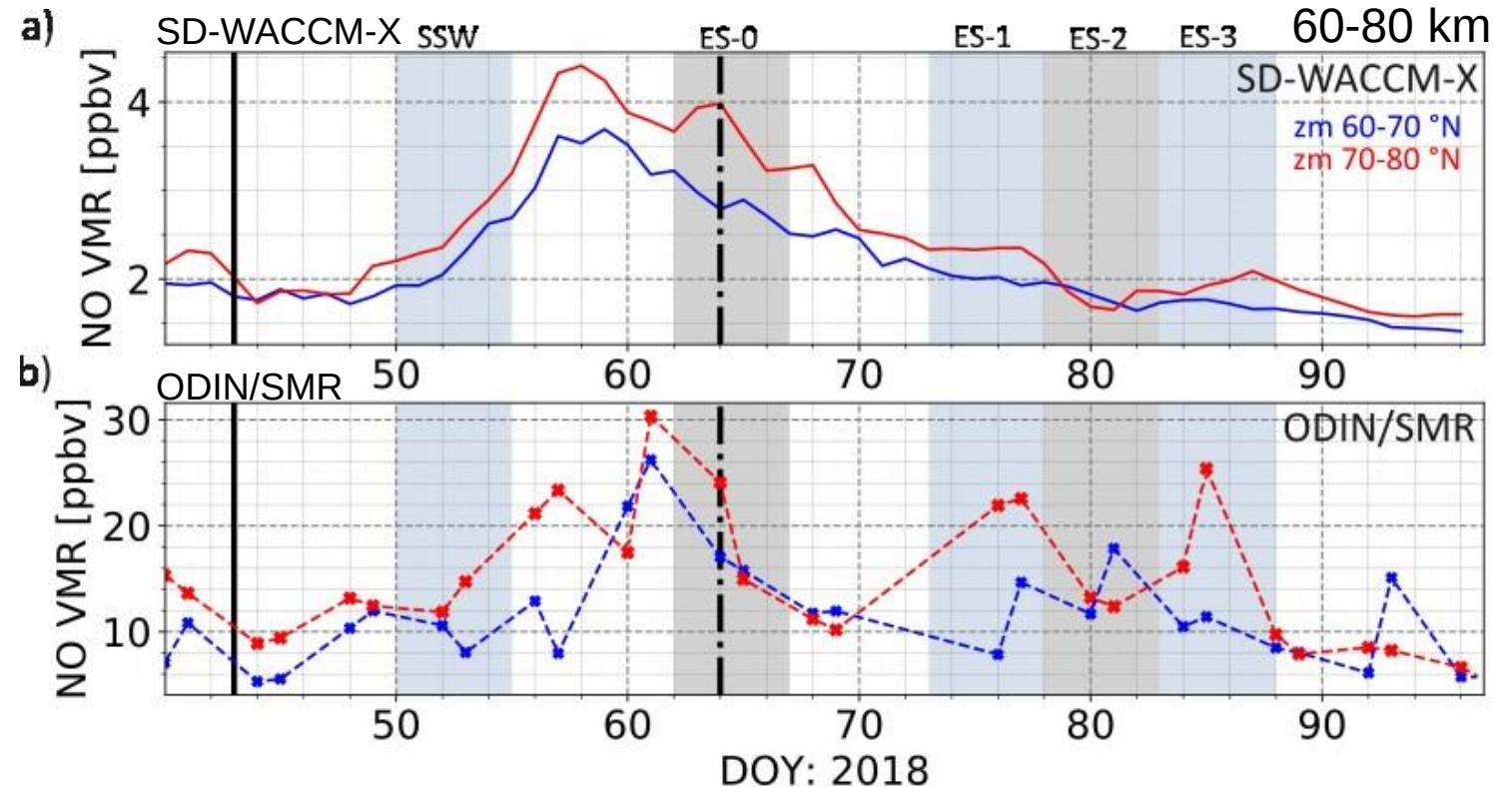
- Temp and H₂O (AURA MLS) averaged along the pathways
- Temp and H₂O show strongest differences during the ES phases and along the **NRK-NYA** pathway



solid lines - 2018
dashed lines - climatology

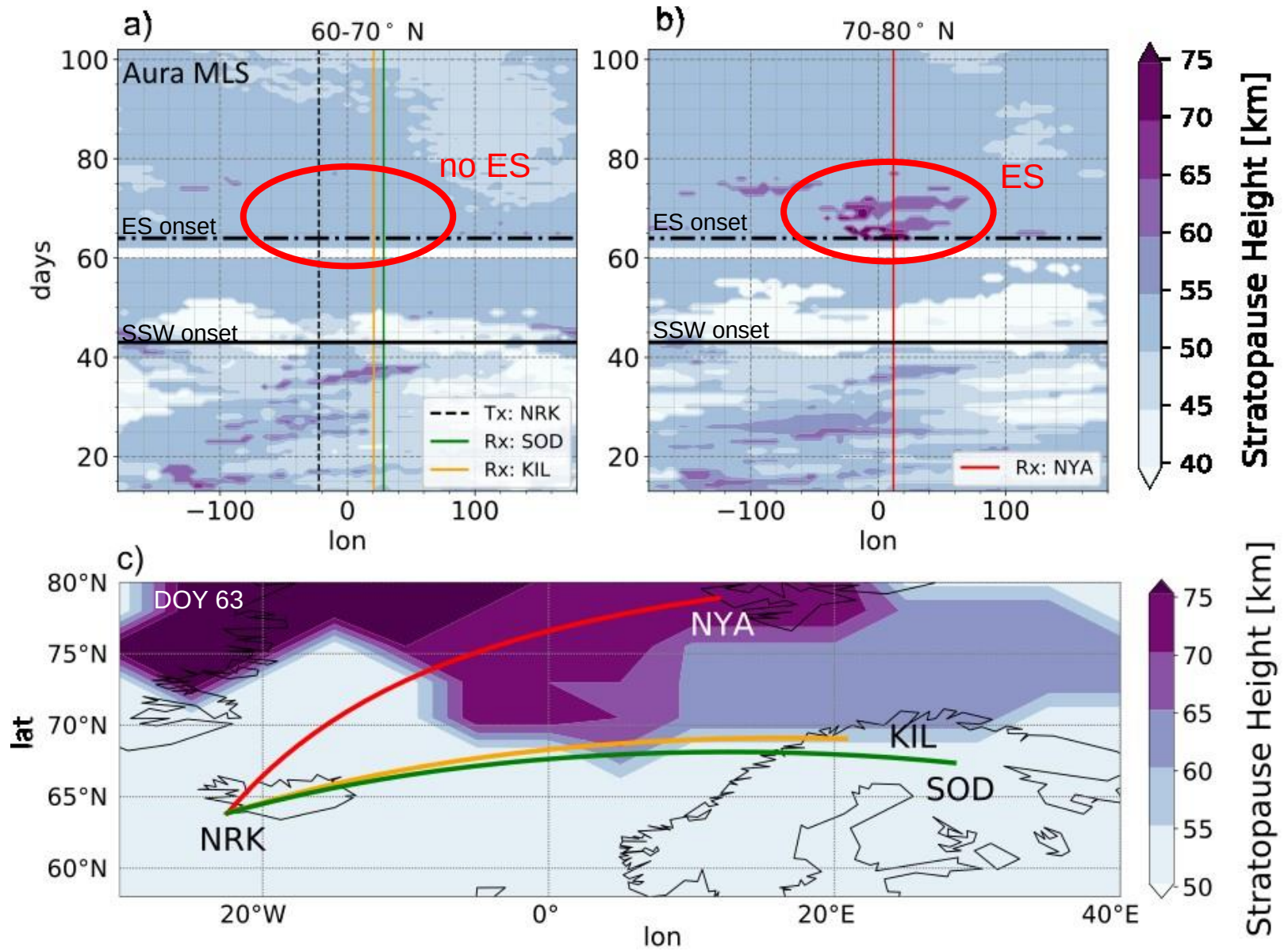
NO by SD-WACCM-X and ODIN/SMR

- zonal mean **60-70°N** and **70-80°N** averaged from 60-80 km are considered, due to low temporal and spatial resolution of ODIN data
- ODIN/SMR NO one magnitude larger
- NO increase starts before ES onset
- 70-80°N shows higher NO during ES-0, ES-1 and ES-3



Stratopause height

- height of stratopause is determined by height of T_{max} between 30 and 90 km
- 60-70°N: stratopause decrease from SSW onset notable
- no increased stratopause height notable around ES onset
- 70-80°N: stratopause decrease from SSW onset notable
- increased stratopause height notable around ES onset between 40°W to + 40°E
- stratopause height at DOY 63: increased height across the NRK-NYA pathway -> NRK-NYA is under stronger influence of ES

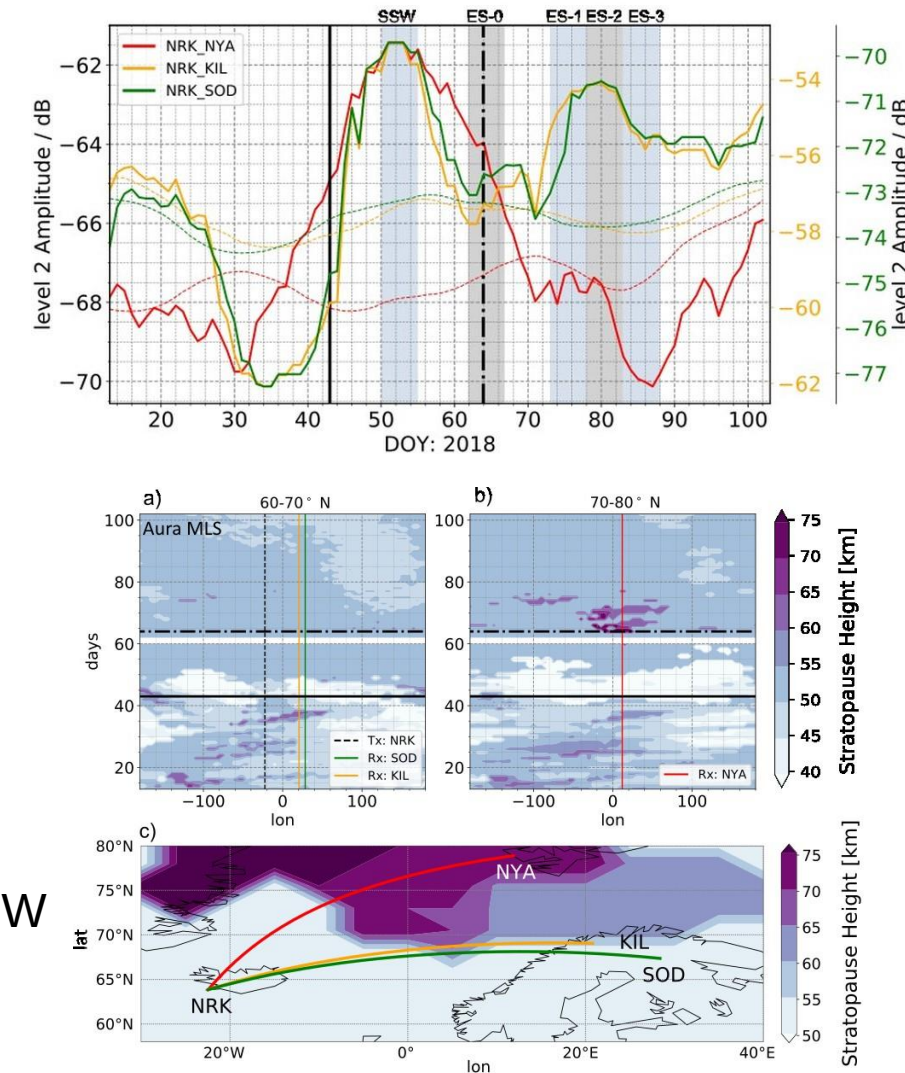


Summary & Conclusion

- VLF signal amplitude variation of three Tx-Rx links: similar during SSW and different during the ES event
- ES event 2018 varies strongly with latitude and longitude
- Characteristical changes in T, H₂O and NO are stronger across the NRK-**NYA** pathway, during the ES phases

Mechanism

- NRK-**NYA**: The increase/decrease of the VLF signal amplitude during the SSW/ES can be explained by the mechanism
- NRK-**SOD/KIL**: The increase of the VLF signal amplitude during the SSW can be explained by the mechanism

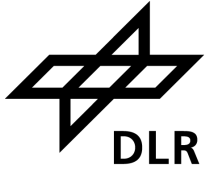


spatial variability of ES event causes that processes, usually leading to VLF amplitude decrease, do not come into force for the links NRK-**SOD** and NRK-**KIL**

Yes, the spatial variability of ES event affects the VLF signal amplitude!

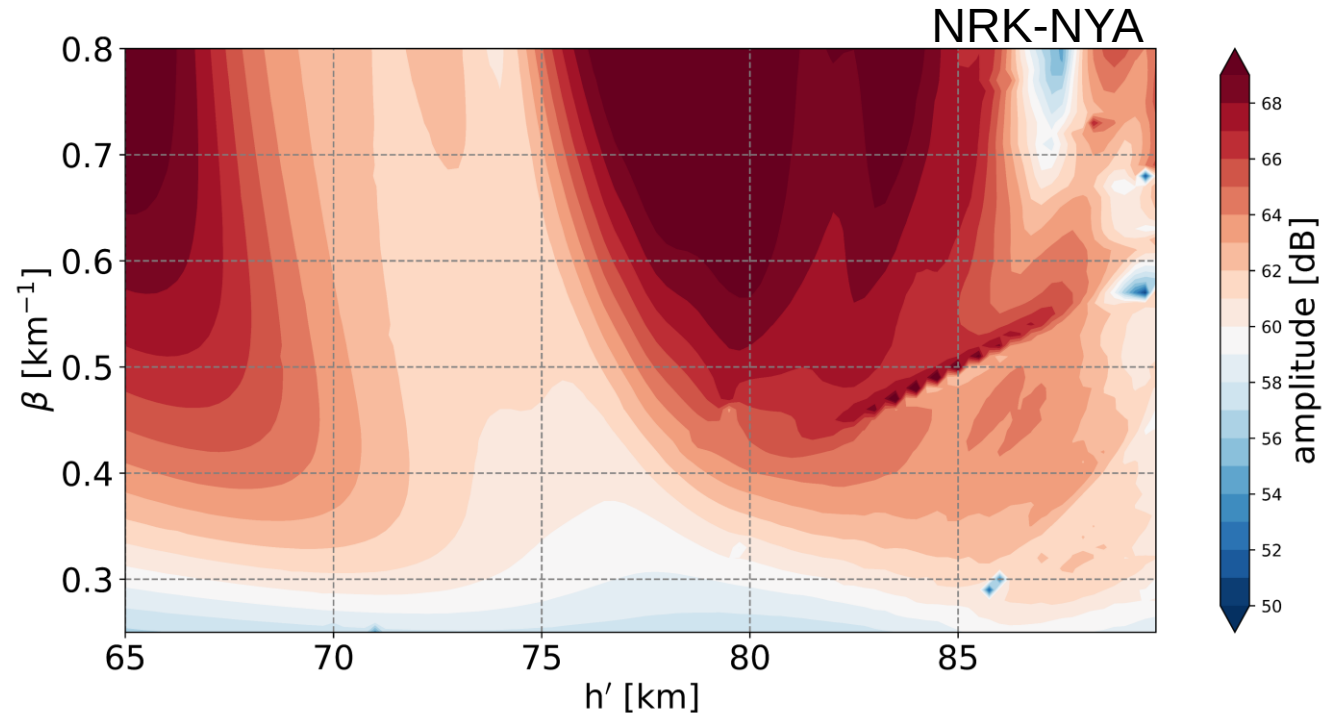
Backup Slides

References



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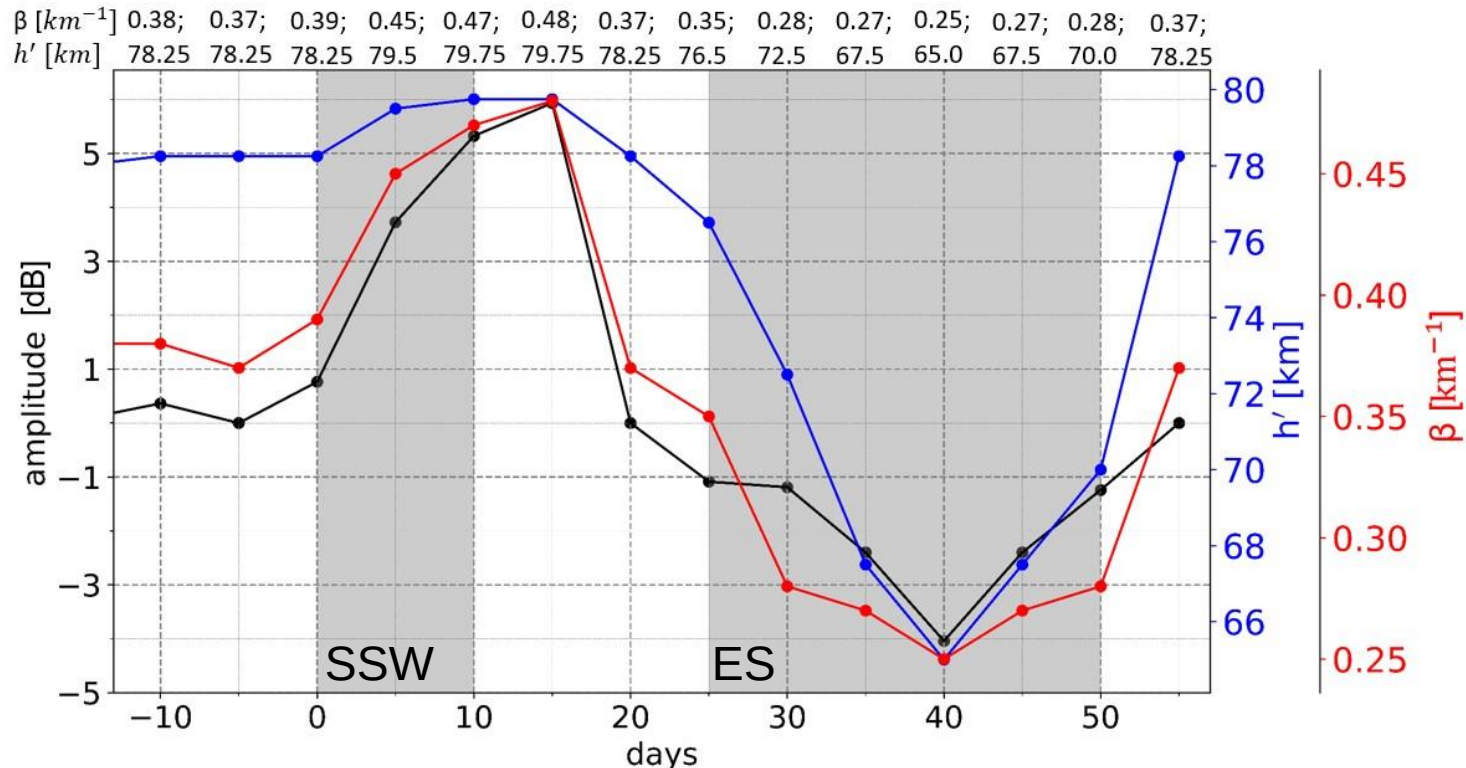
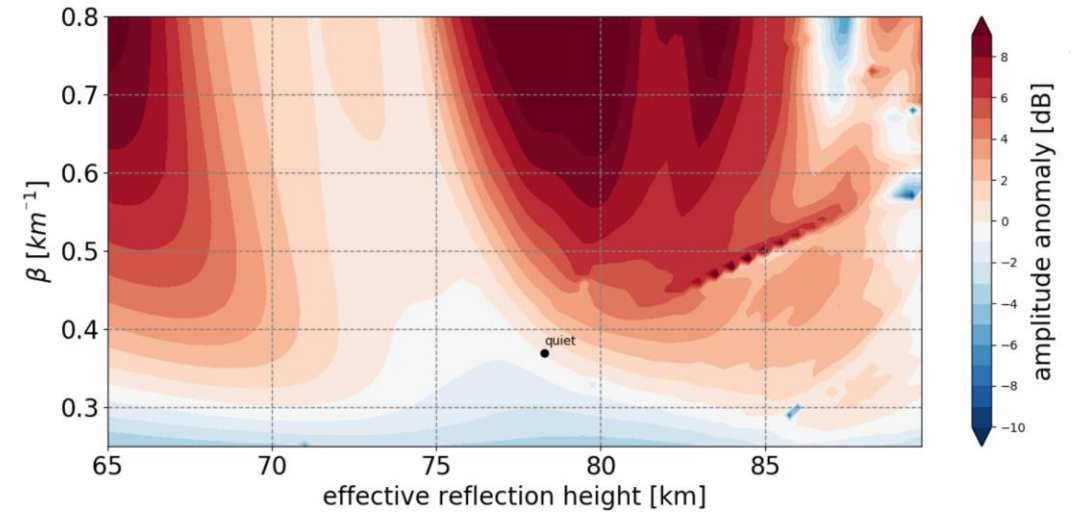
Parameter space



- LWPC: parameter space assigns amplitude for each β and h' combination

Validation with the Long Wavelength Propagation Capability (LWPC) code

- LWPC: parameter space assigns amplitude for each β and h' combination
- amplitude anomaly = amplitudes in the parameter space - the quiet day amplitude ($\beta = 0.37$, $h' = 78.3$ km, for 30 kHz in high latitudes [Ferguson (1998)])
- due to the ambiguity, clear assignment of amplitude anomaly one pair of β and h' is not possible



- reproduction of observed amplitude changes during the SSW/ES 2009 with modifications of β and h' which were assumed in the mechanism

Equations Mechanism

D-region, below 90 km:

- recombination is indirectly dependent to T:

$$\alpha_{\text{eff}} \propto \left(\frac{T_e}{300} \right)^{-0.5} \quad [\text{Bajčetić et al. (2017)}]$$

- collision frequency is directly dependent to T:

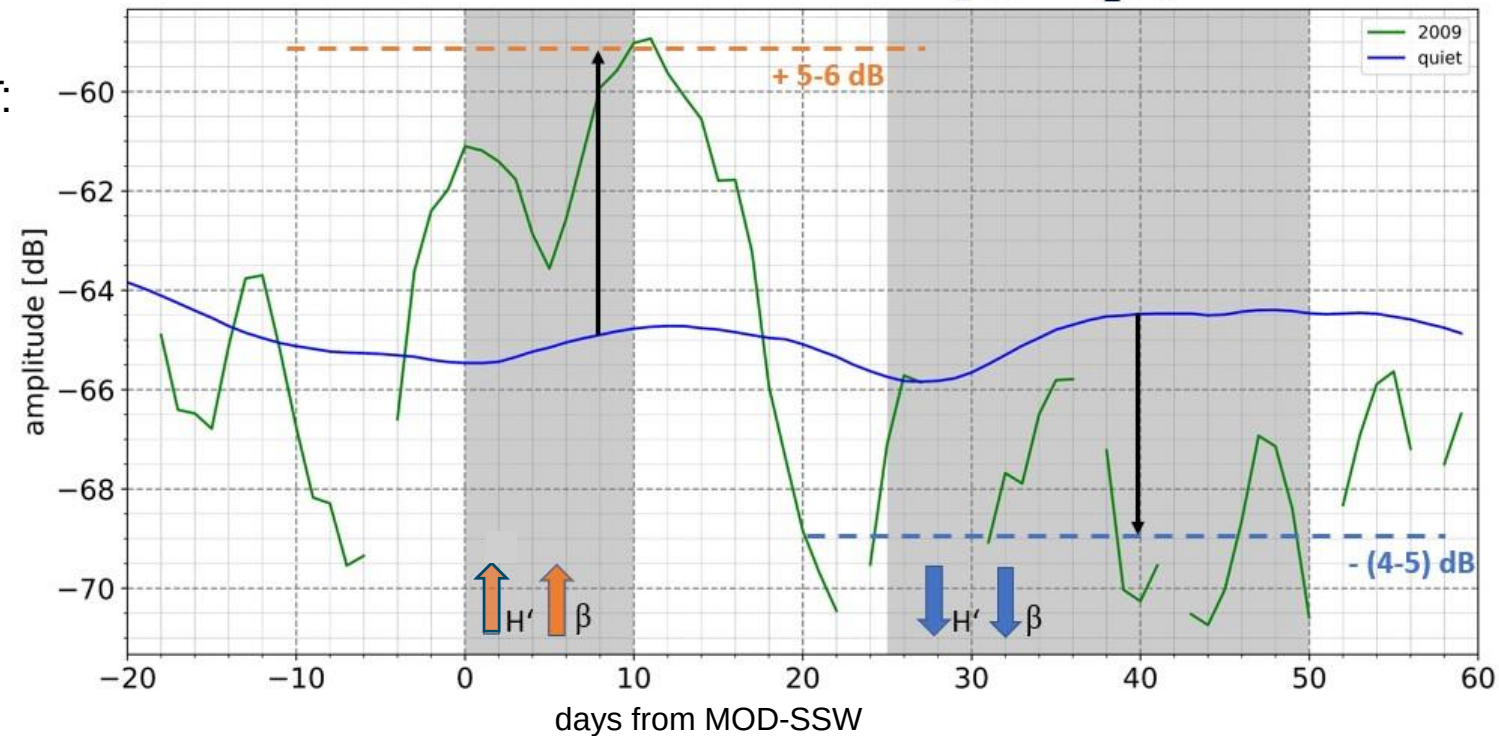
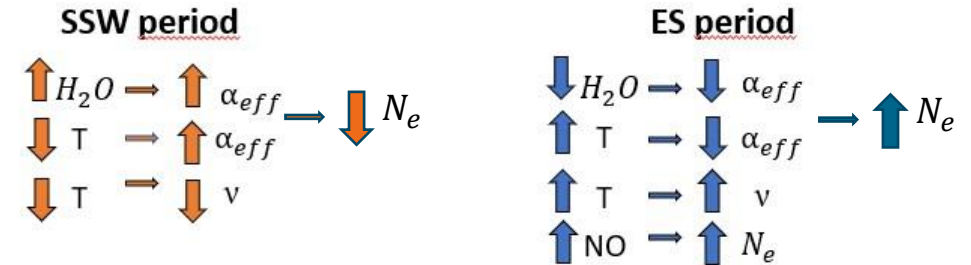
$$\nu(h) = 1.21 \cdot 10^8 \cdot p_0 \cdot e^{\frac{-g \cdot M \cdot h}{R \cdot T(h)}} \cdot s^{-1} \quad [\text{Vuthaluru et al. (2002)}]$$

- water-cluster ions in D-region with high recombination rate:

$$N_e \propto \frac{1}{H_2O} \quad [\text{Sodankylä Ion and Neutral Chemistry Model}]$$

VLF-signal:

- controlled by the gradient of the vertical N_e profile sharpness (β) + the effective reflection height h'
- VLF signal absorption $\propto \nu$ [Macotela et al., 2021]



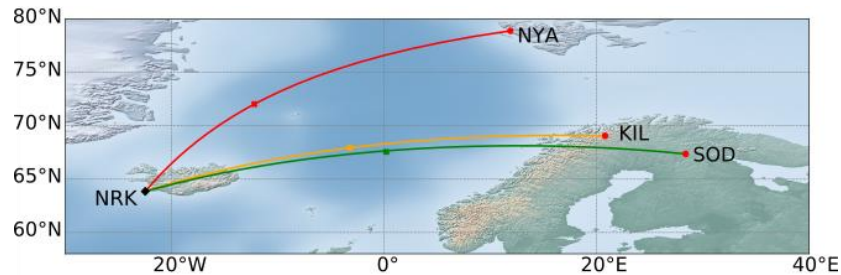
↓ ν → ↓ absorption

amplitude
increase

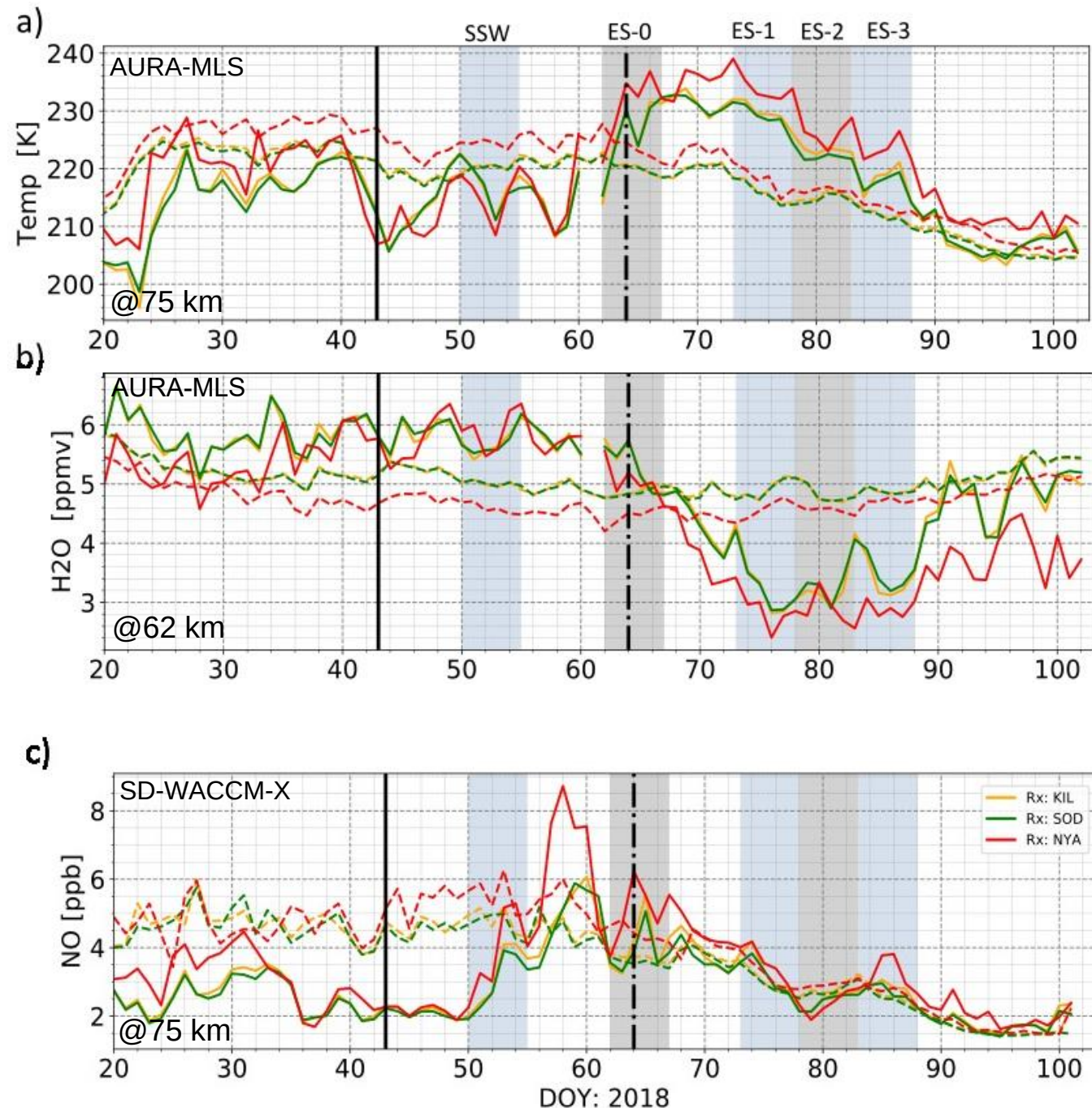
↑ ν → ↑ absorption

amplitude
decrease

Atmospheric Parameters



- averaged along the pathways
- Temp and H₂O show strongest differences during the ES phases and along the **NRK-NYA** pathway
- Differences in NO variation are strongest between phases SSW and ES-0 along **NRK-NYA**
- **NRK-NYA**: slightly higher NO during ES-0 and ES-3
- be aware, model data no observations!

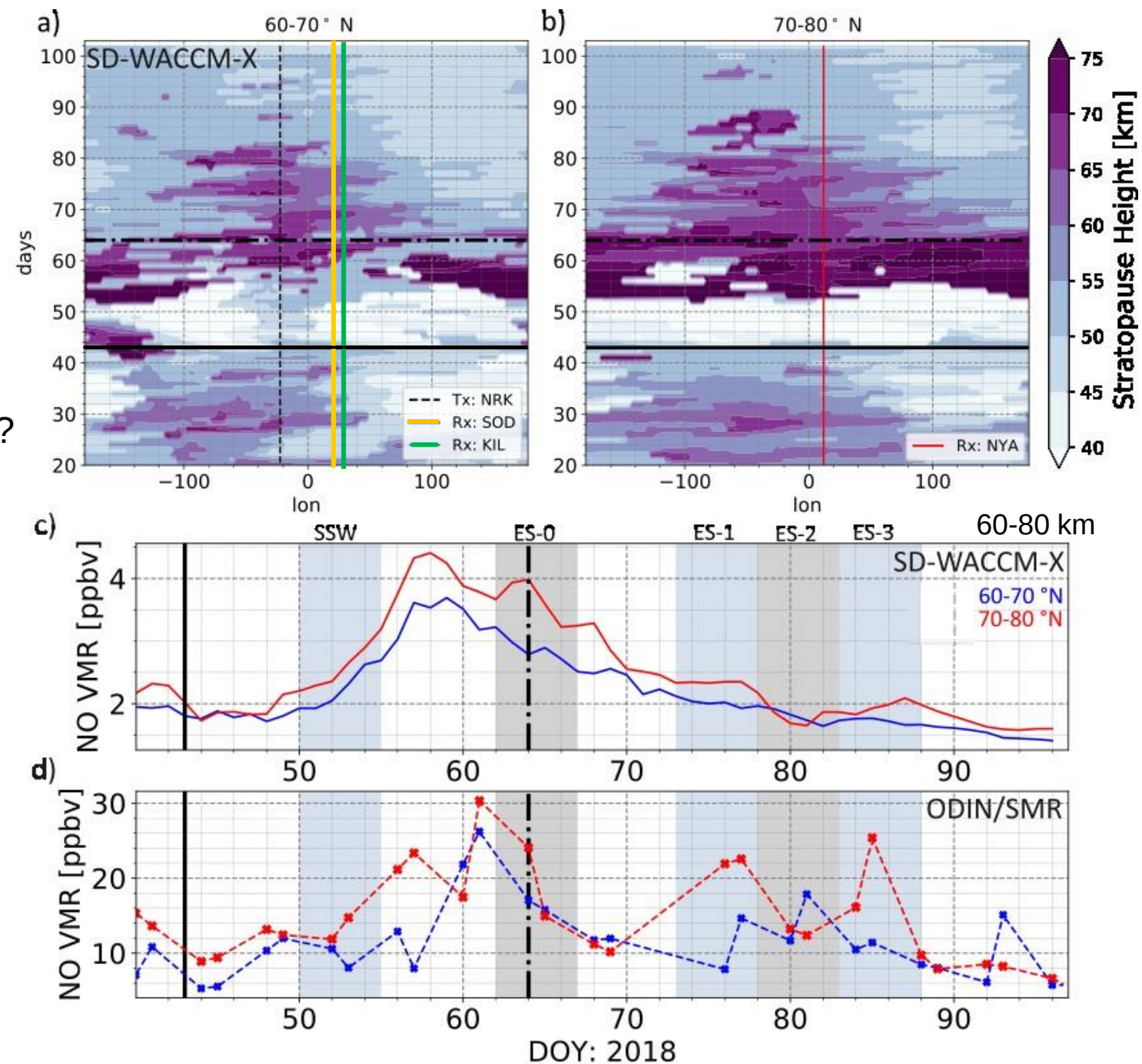


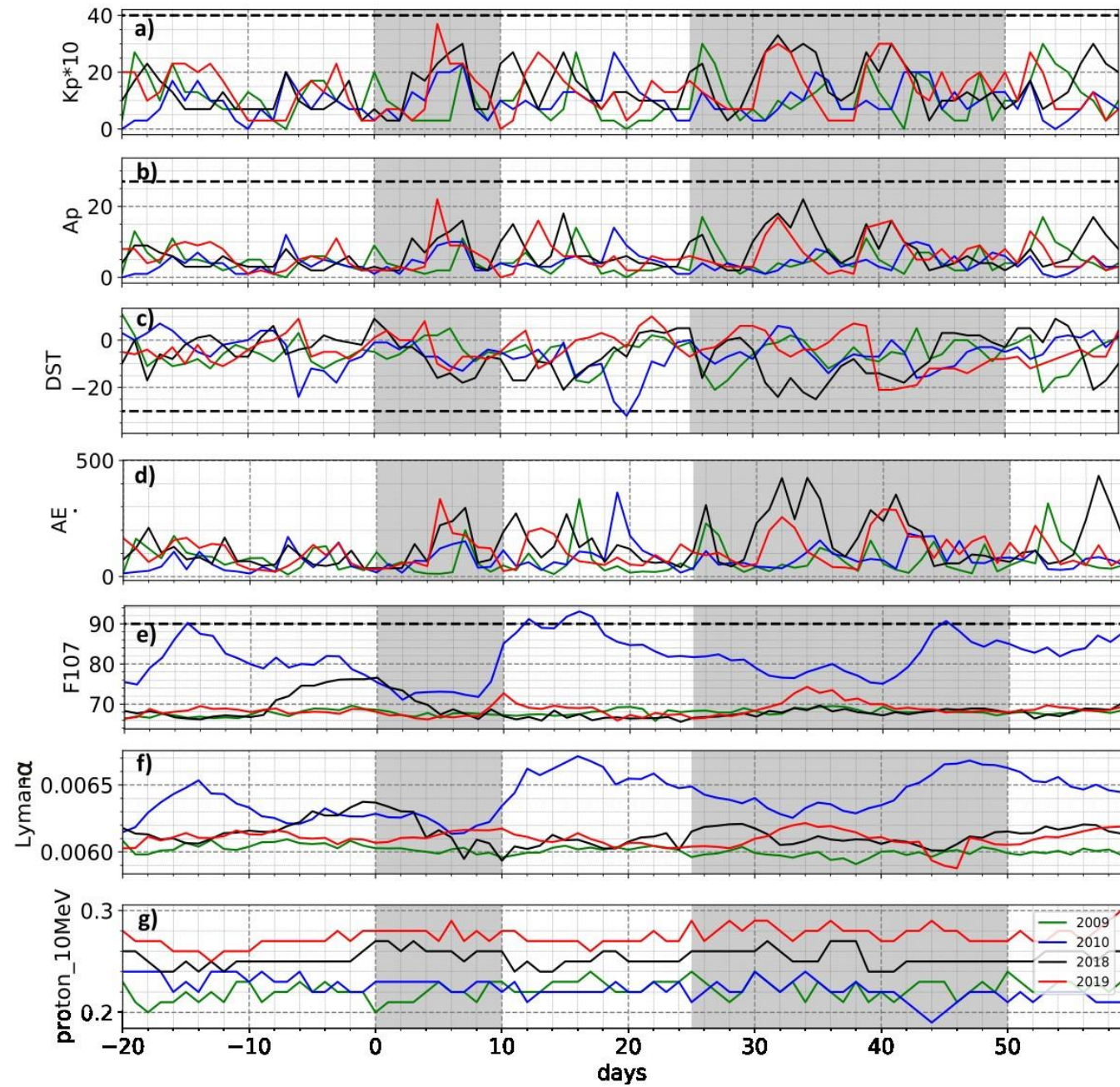
WACCM-X data

- Significant difference to spatial variability of the ES determined with Temp from MLS
- SD-WACCM-X does not capture the characteristics of the ES 2018

→ Can we trust the NO from SD-WACCM-X?

- Comparison with NO measurements from ODIN/SMR
- ODIN/SMR NO one magnitude larger
- zonal mean 60-70°N and 70-80°N averaged from 60-80 km are considered, due to low temporal and spatial resolution of ODIN data
- Both: NO increase starts before ES onset
- 70-80°N shows higher NO during ES-0, ES-1 and ES-3





VLF Data processing – level 2

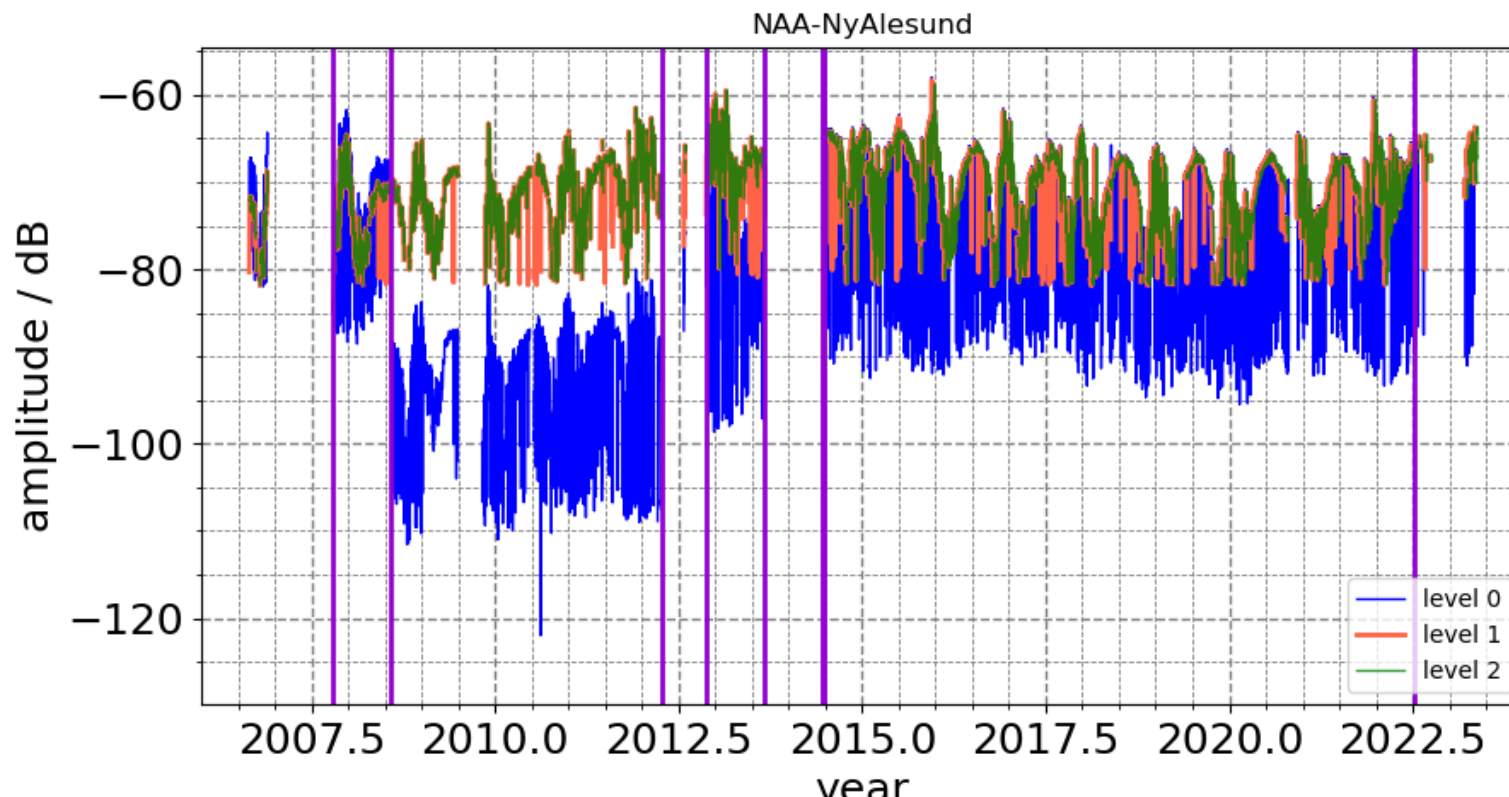
Level 0:
10 min median
of raw data



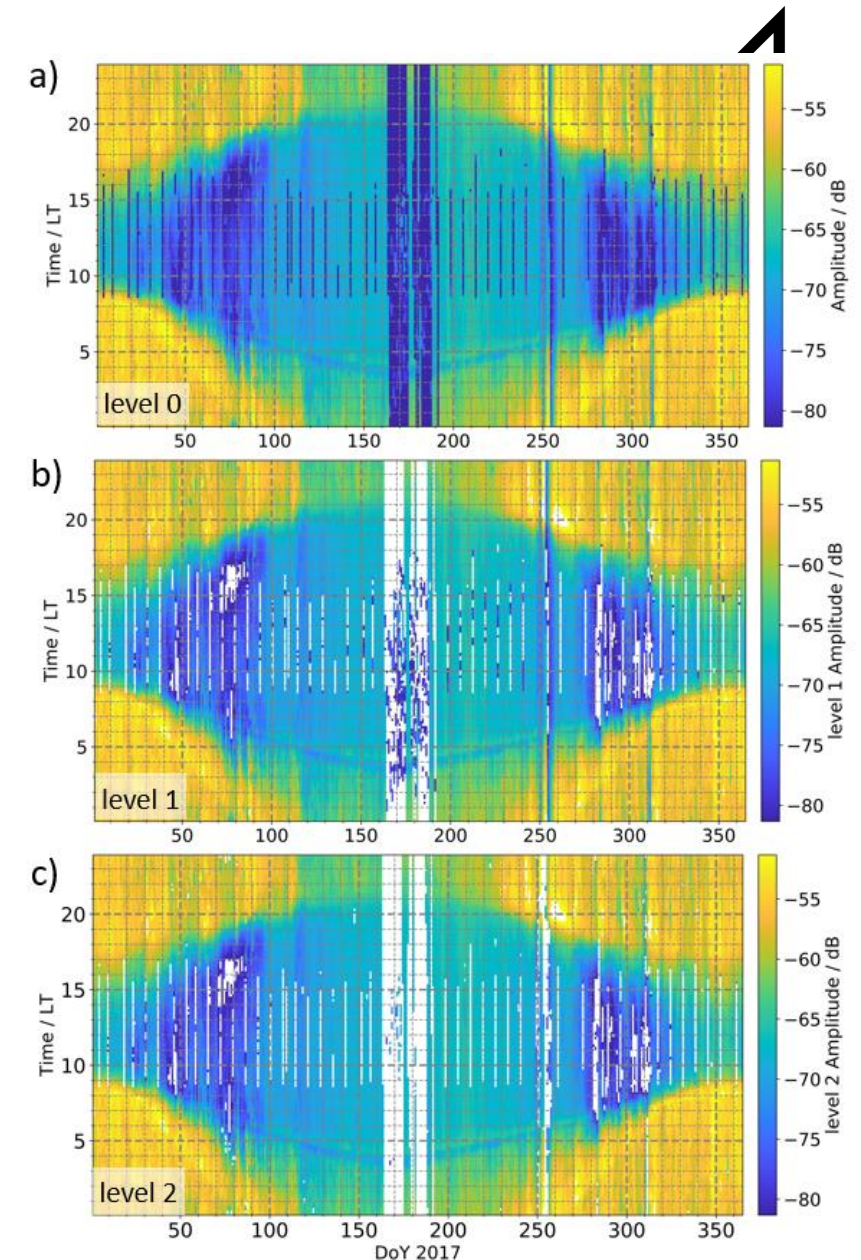
Level 1:
Leveling +
bandpass outlier
filtering



Level 2:
Outlier filter with
2D- MAD

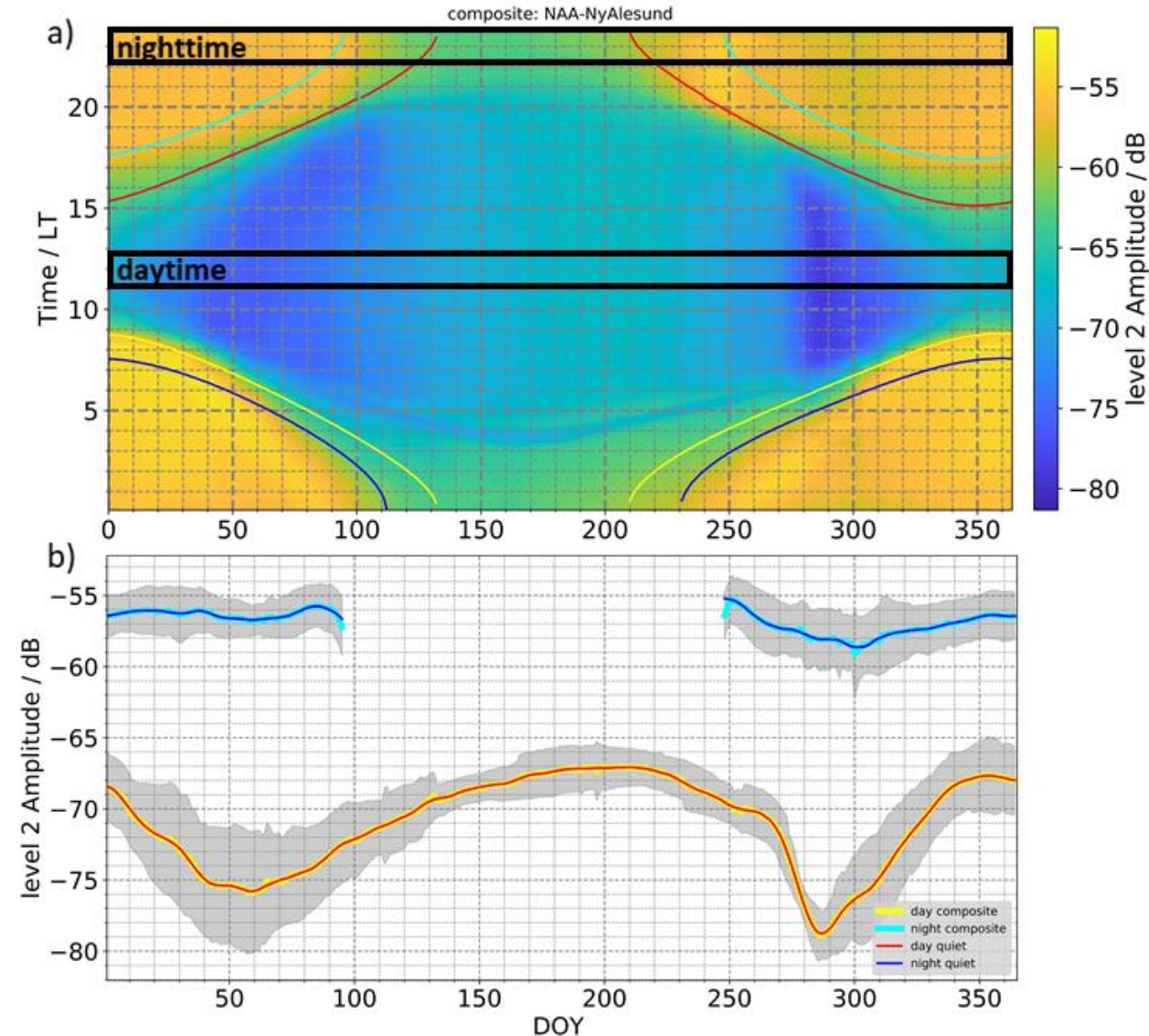


Note, due to leveling the solar cycle cannot be considered with certainty!



VLF Data processing - Quiet time line

- Composite of level 2 data
 - Daytime: median (12 LT $\pm$ 1h)
 - Nighttime: median (23LT $\pm$ 1h)
 - Smoothing with Savitzky-Golay filter (17,3)
 - To distinguish between typical seasonal variation and disturbances of VLF amplitude
-
- Night: values between dark night (cyan) to nautic twilight (dark blue)
 - Day: values between civil twilight (yellow) and nautic twilight (red)



Daytime and Nighttime

- Night: values between dark night (cyan) to nautic twilight (dark blue)
- Day: values between civil twilight (yellow) and nautic twilight (red)

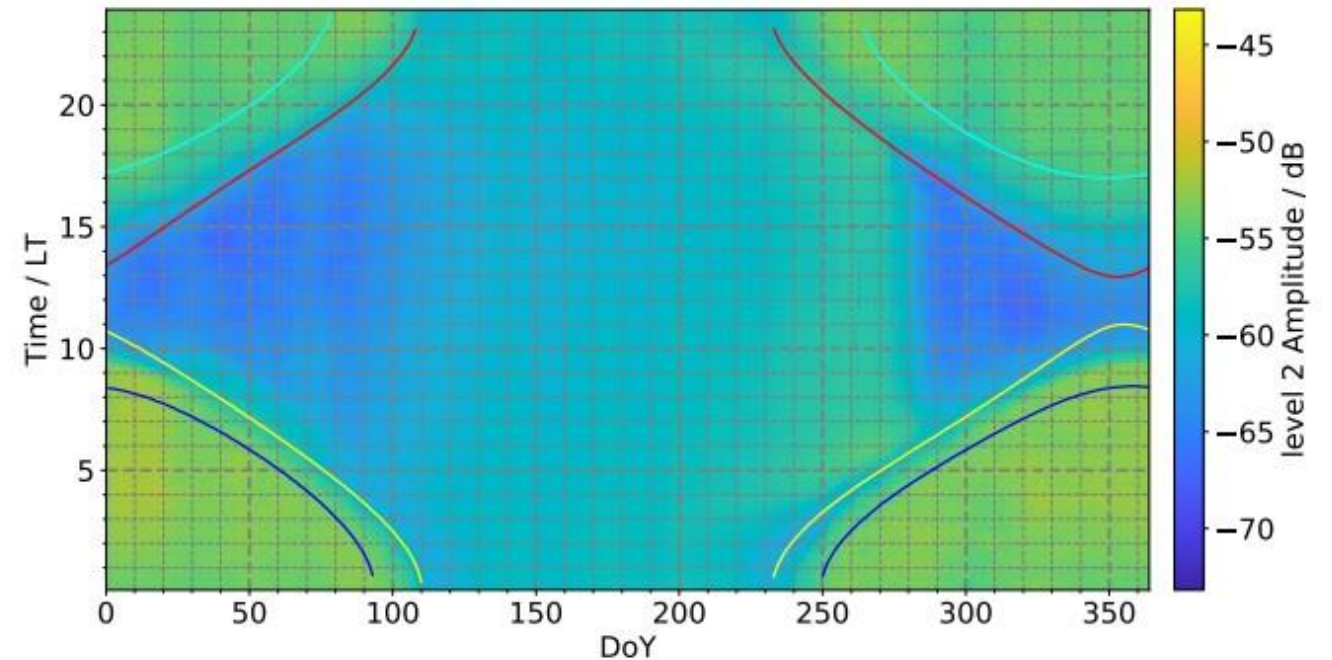
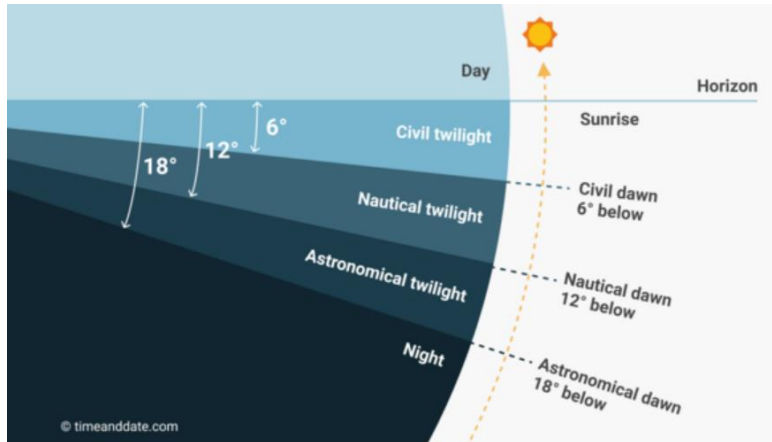
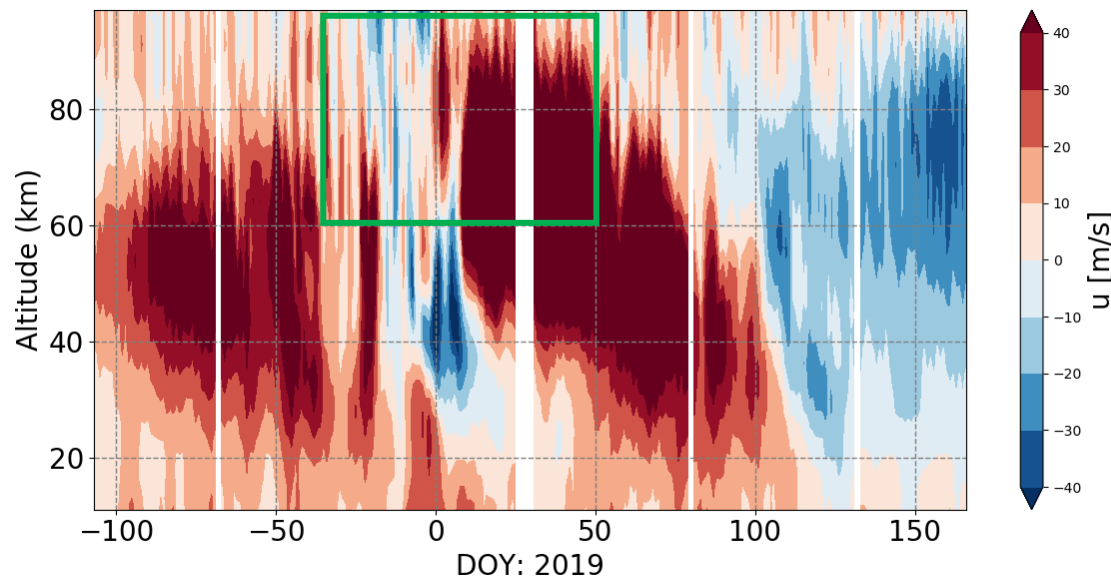
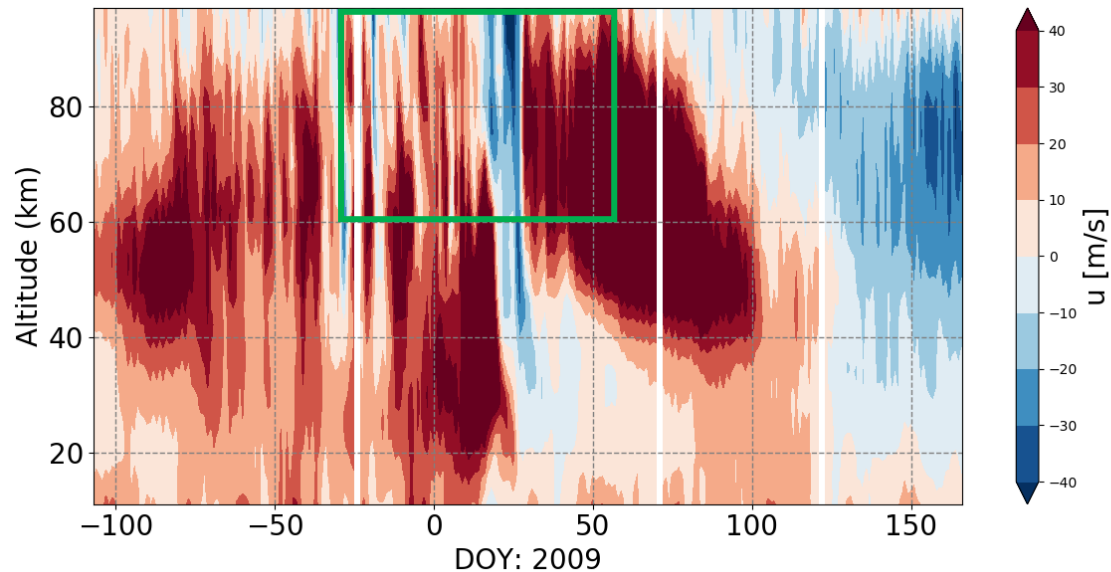


Figure S5. Composite of the diurnal and seasonal variation of the VLF signal amplitude for the link between NRK-NYA. Colored lines represent different states of SZA: cyan for dark night ($\text{SZA}=108^\circ$), dark blue for nautical twilight dawn ($\text{SZA}=102^\circ$), yellow for civil twilight ($\text{SZA}=96^\circ$), and red for nautical twilight dusk ($\text{SZA}=102^\circ$). Local time (LT) refers to the midpoint position.

Mesospheric Onset Day of SSW and ES event



- temporal and vertical development are different for single SSW events
- Wave breaking in the mesosphere causes higher variability in temperature and wind
- Determination of Mesospheric Onset Day at a fixed altitude is error prone due to diversity of SSW events -> altitude range
- MOD-SSW and MOD-ES defined by fulfillment of specific conditions of following parameters:

u (zonal wind)

$$u_{std} = \frac{u - \bar{u}}{std(u)}, \quad T_{std}$$

$$\Delta T_{SSW_{std}} = \frac{\Delta T_{SSW} - \overline{\Delta T_{SSW}}}{std(\Delta T_{SSW})} \quad \text{with} \quad \begin{aligned} \Delta T_{SSW} &= T(40\text{km}) - T(70\text{km}) \\ \Delta T_{ES} &= T(65\text{km}) - T(80\text{km}) \end{aligned}$$

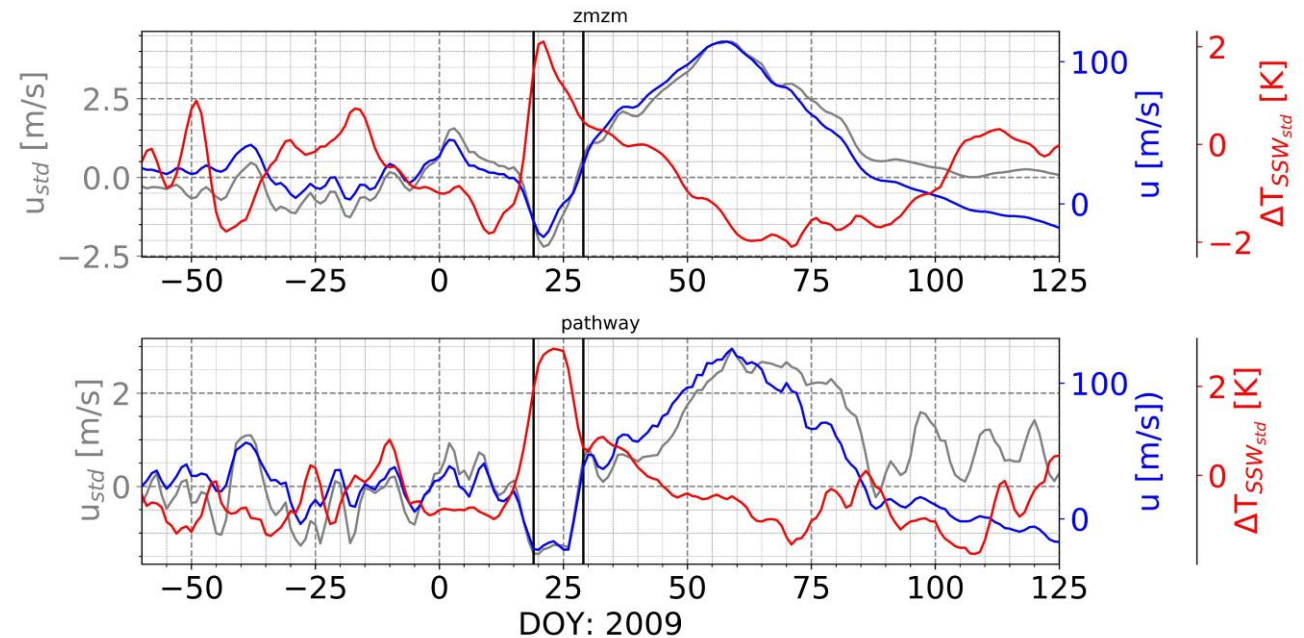
Mesospheric Onset Day of SSW and ES event

- **MOD-SSW**

- altitude range (60-80 km) and not at a fixed altitude
- zonal 60-80°N: $u < 0 \text{ m/s}$, $\Delta T_{SSW_{std}} \geq 1$, $u_{std} \leq -0.8$
- path: $u < 0 \text{ m/s}$, $\Delta T_{SSW_{std}} \geq 1$, $u_{std} \leq -1$
- MOD-SSW: first day between Nov-May when zonal and path conditions match
- end SSW: $u \geq 0 \text{ m/s}$, $\Delta T_{SSW_{std}} < 1$

- **MOD-ES**

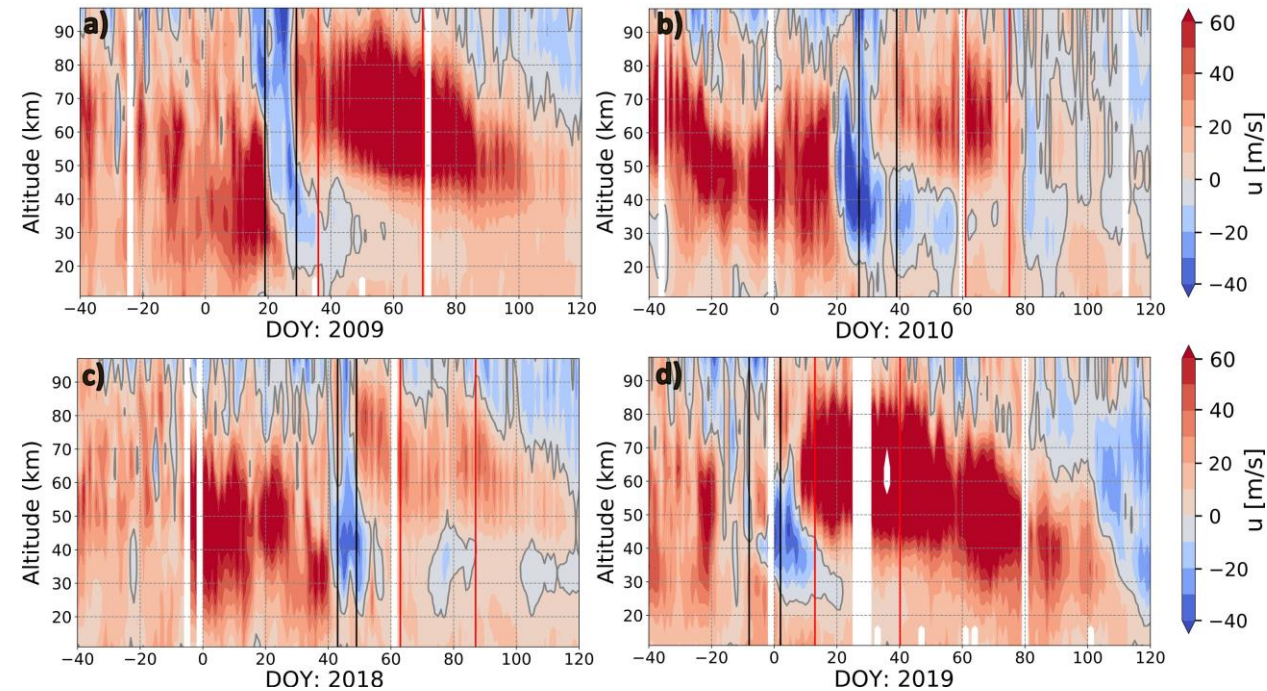
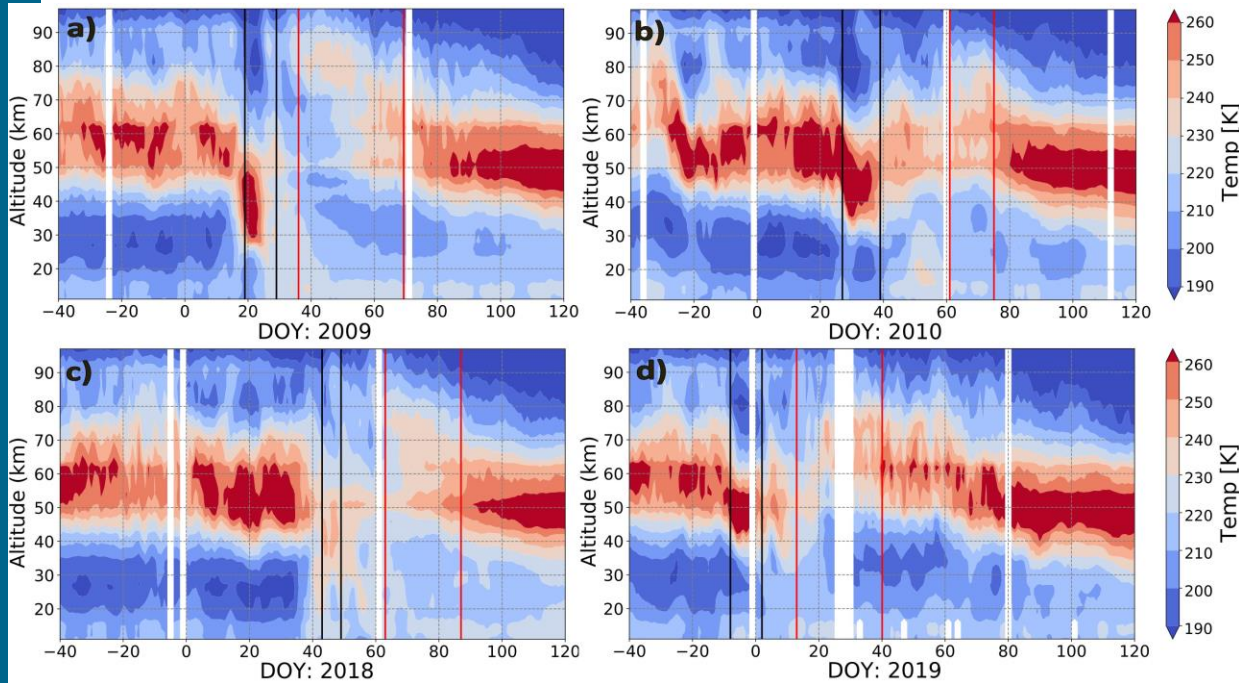
- altitude range (70-80 km)
- conditions must apply only at the pathway
(ES events often show a longitudinal structure likely determined by zonally asymmetric GWD)
- MOD-ES: first day after MOD-SSW when
 $u_{std} \geq 0.5$, $u > 20 \text{ m/s}$, $T_{std} \geq 0.8$, $\Delta T_{ES_{std}} \leq -1$
- end ES: $\Delta T_{ES_{std}} \geq 0$, $20 \text{ m/s} < u < 50 \text{ m/s}$



Temporal development over altitude of the temperature and the zonal wind during the four SSW/ES events

temperature

zonal wind



SSW/ES events

- Definition of **M**esospheric **O**nset **D**ay for **SSW** and **ES** (MOD-SSW, MOD-ES) and duration of SSW and ES events by specific conditions of the zonal wind and temperature
- Only SSW/ES events under low/moderate solar and geomagnetic conditions are considered -> **only 4 events**

year	MOD-SSW	Duration SSW	MOD-ES	Duration ES
	DOY	days	DOY	days
2009	19	10	36	33
2010	27	12	61	14
2018	43	6	63	24
2019	-8	10	13	27

- the 4 events are centered at their individual **MOD-SSW** (day 0)
- SSW period: 0-10 days from MOD-SSW
- ES period: 25-50 days from MOD-SSW

MOD-SSW

